

Correlation of Limestone Properties with Bit Performance Variables for LIMROCKWARE2010 Development

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Abstract- This paper correlates selected properties of limestone with tri-cone bit performance variables for developing LIMROCKWARE2010. In order to achieve these objectives rock samples were collected and uniaxial compressive strength, tensile strength and chemical composition tests were carried out on these samples. The length of the insert buttons on the surface of the drill bits were measured using digital vernier caliper at regular interval. Also, the tooth and bearing wear rate as well as the penetration rate were determined on the field. The results of the uniaxial compressive strength varied from 86.5 MPa to 112 MPa. Hence, the strength characteristic of these rocks varied from medium to high strength limestone. The Equivalent Quartz Content (EQC) of the rock samples also varied from 17.37% to 36.676% while the Rock Abrasivity Index (RAI) varied from 15.03 to 43.317. The results of statistical correlation matrix revealed that uniaxial compressive strength, tensile strength, silica content, Equivalent quartz content and rock abrasivity index are dominant rock properties affecting performance variables, having high coefficient of correlation. The developed regression equation for predicting penetration rate, tooth wear rate and bearing wear rate for limestone are given as $Pr = 4.583 - 1.052T + 0.029EQC + 0.046SiO_2$, $W_G = -8.127 + 2.7T - 1.29EQC - 0.024SiO_2$ and $W_B = -10.296 + 3.453T - 0.203EQC - 0.027SiO_2$ respectively. The regression models formulated were used for the development of LIMROCKWARE2010 which will compute the penetration rate, tooth and bearing wear rate, depth drilled per metre, estimate number of bits required and cost of drilling per metre when necessary rock input are supplied.

Keywords- Limestone; Quartz; Correlation; Bit; Variables; Strength

I. INTRODUCTION

Generally, rock is drilled blasted, loaded, hauled to primary crusher and then transported to be further processed [1]. The performance of a particular bit in any formation is dependent on the properties of rock material and drill operating parameters. Thus, a bit will perform poorly in an inappropriate formation whose properties have not been established. Ultimately, the most influencing parameter for bit performance is the physico- mechanical property of the rock which greatly influences the penetration mechanism of whatever bit used for drilling [2]. They form the resistance and alliance that the bit must overcome before optimum penetration can be achieved. These include hardness, strength, texture, elasticity, plasticity, abrasiveness, structure and the characteristic of breakage. The chemical and mineral composition of the rock also plays a role as it affects the performance of the drill bit [2]. The performance of a bit could be determined and measured based on its rate of penetration, bit life and bit wear rate [3]. The rate of penetration denotes the depth penetrated per unit time while the wear rate describes the velocity of material removal from the bit and it a basic factor for the calculation of bit consumption and wear costs. A

detailed study of the empirical relationship between the performance variable (rate of penetration, bit life and bit wear rate) and the various rock properties for different drilling parameters is required to perform economical and efficient drilling [4]. Bit performance analysis requires the statistical correlation matrices of the bit variables (such as bit life, bit wear rate, rate of penetration) with tested rock properties (Ersoy and Waller, 1995). The results can be used for performance analysis, wear characteristics and mechanism (like wear rate index), model development, performance prediction of various bits using multi variable analysis. It is therefore, desirable to establish the relationship between the performance variables and rock properties of the formation in order to predict the longevity of the bit and ultimately provide information for better drilling operations in limestone quarry.

II. MATERIALS AND METHOD

The study area covers Ewekoro limestone deposit in Ewekoro local government of Ogun State. It is located on latitude of 6°53'N and longitude of 3°12'E which is presented in Fig. 1



Fig. 1 Map of Nigeria Showing Ewekoro

A. Determination of Uniaxial Compressive and Tensile Strength

The UCS test procedure was in accordance with [5] and [6] and was determined using Eq. 1 the results are presented in Table I.

$$Co = \frac{P}{A} = \frac{P}{W \cdot D} \quad (1)$$

Where Co = Uniaxial compressive strength. MPa, P = the applied peak load, (kN), W = Width of the sample (mm), D = Height of the sample (mm). The tensile strength of the rock samples was estimated based on the formulae suggested by [7] and [5] which shows the general relationship between the

compressive strength (C_o), the point load strength (I_s) and the tensile strength (T_o), as expressed in Eq. 2 and the results are presented in Table 1.

$$C_o = 20T_o = 30 I_s \quad (2)$$

B. Determination of Chemical Composition

The samples for X-Ray Florescence analysis were prepared in accordance with [8] and the results of the analysis of major elements present in the samples are presented in Table II.

TABLE I MEAN OF COMPRESSIVE (C_o) AND TENSILE (T_o) FOR THE FORMATION CLASSIFICATION

Sample Codes	C_o (MPa)	T_o (MPa)	Classification of Rock Strength (Deere and Miller, 1966)
PAN1	86.5	4.31	Medium Strength
PAB1	89.2	4.46	Medium Strength
CEM1	95.8	4.79	Medium Strength
GLAB	112	5.6	High Strength

TABLE II CHEMICAL COMPOSITION OF LIMESTONE FORMATIONS

COMPOSITION	GLAB (%)	CEM1 (%)	PAB1 (%)	PAN1 (%)
SiO ₂	13.920	9.873	3.653	3.628
Al ₂ O ₃	1.880	0.613	1.240	1.043
Fe ₂ O ₃	7.530	1.308	1.250	1.258
CaO	33.66	48.108	51.050	51.540
MgO	4.560	0.403	1.350	1.105
Na ₂ O	0.080	0.640	0.048	0.018
K ₂ O	1.510	0.045	0.093	0.075
SO ₃	0.070	1.000	0.088	0.085
LOI*	31.400	36.350	41.54	41.668

NOTE: * --- Lost on ignition, ** --- Silica ratio, *** --- Alumina ratio

C. Determination of Rate penetration

The rate of penetration was determined using Eq. 3. In addition penetration rate could be affected by packing density [10].

$$ROP = \frac{\text{Total depth drilled}}{\text{Time taken}} \quad (3)$$

Where ROP is Rate of Penetration.

The summary of rate of penetration are shown in Table III for all bits

TABLE III AVERAGE ROP IN EACH FORMATION

ROCK CODE	BIT01 (m/min)	BIT02 (m/min)	BIT03 (m/min)	BIT04 (m/min)	BIT05 (m/min)	AVE ROP (m/min)
GLAB	0.31934	0.3199	0.3068	0.3709	0.3289	0.38919
CEM1	0.5893	0.6477	0.5308	0.5843	0.5799	0.58642
PAB1	0.6552	0.6593	0.5668	0.6199	0.5949	0.61922
PAN1	0.7151	0.7487	0.7011	0.7105	0.7172	0.71852

D. Determination of Equivalent Quartz Content and Rock Abrasivity Index

The equivalent quartz content (EQC) of the rock samples were determined in accordance with [9] as shown in Eq. 4 and the summary of the result is presented in Table 4 Where A = mineral amount (%), R = Rosiwal abrasiveness value and n = number of mineral, Also, the rock abrasivity index (RAI) of the samples were determined as suggested by [3] and expressed in Eq.5. The summary of the results are presented in Table IV.

$$EQC = \sum_{i=1}^n A_i R_i (\%) \quad (4)$$

$$RAI = C_o \times \frac{EQC}{100} \quad (5)$$

Where, RAI = Rock Abrasivity Index; C_o = Uniaxial compressive strength and EQC = Equivalent Quartz Content

TABLE IV EQC AND RAI OF THE SAMPLES

Samples	C_o (MPa)	EQC (%)	RAI
PAN1	86.5	17.37	15.03
PAB1	89.2	19.35	17.26
CEM1	95.8	20.43	19.57
GLAB	112.0	36.68	43.32

E. Determination of Bearing Wear Rate

The bit wear rates for the tooth wear and bearing wear were estimated by dividing either the tooth wear or bearing wear by the total depth drilled by individual drill bit. The summary of the corresponding average tooth wear rate and bearing wear rate for each drill bit is presented in Table V.

TABLE V AVERAGE TOOTH AND BEARING WEAR RATES

Bit Type	Depth Drilled/Bit (km)	Average Tooth Wear Rate (mm/km)	Average Bearing Wear Rate (mm/km)
BIT01	3.270	0.9337	0.6891
BIT02	2.280	1.1813	0.9152
BIT03	1.600	2.0833	2.0042
BIT04	1.500	2.1778	1.5067
BIT05	2.100	1.2000	0.9905

III. RESULTS AND DISCUSSION

A. Correlation of Rate of Penetration with Rock Properties

The correlation between the rate of penetration and uniaxial compressive strength is shown in Figure 2. From this graph, there exists a perfect correlation between the ROP and UCS. correlation between ROP and tensile Strength. The relationship of tensile strength with rate of penetration is presented in Figure 3. A good correlation exists such that a decrease in ROP is seen as the tensile strength increases. Correlation between ROP and Equivalent Quartz Content The relation between equivalent quartz content and ROP is given in Figure 4. The graph indicates that there is a reduction in ROP as EQC increases.

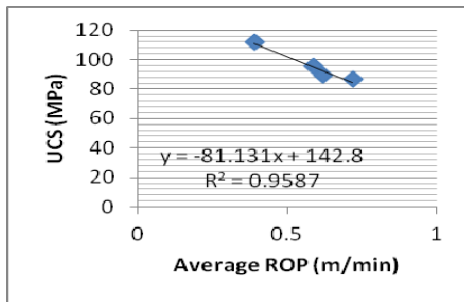


Fig. 2 Uniaxial compressive strength and ROP

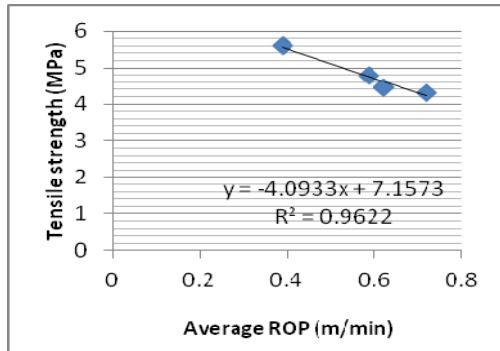


Fig. 3 Tensile strength and ROP

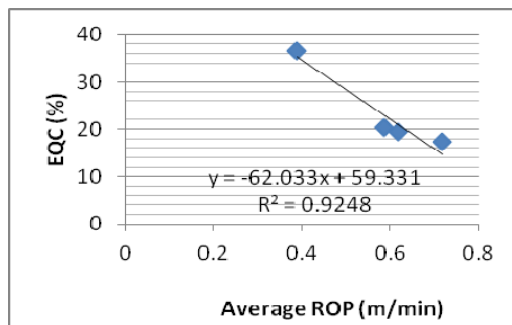


Fig. 4 Equivalent quartz content (EQC) and ROP

B. Correlation between Rate of Penetration and Abrasivity Index

The correlation between the rate of penetration and the rock abrasivity index is presented in Figure 5 and this indicates that increasing rock abrasivity index reduces the rate of penetration of tri-cone bits.

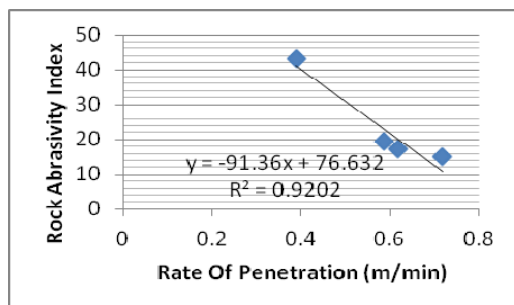


Fig. 5 Rock Abrasivity Index and ROP

C. Correlation of Wear Rate with Rock Properties

The relationship between the rate of tooth wear and the uniaxial compressive strength is shown in Figure 6. The graph indicates that as uniaxial compressive strength increases the tooth wear rate of the bit increases as well.

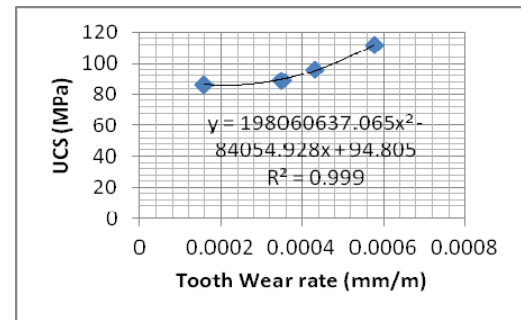


Fig. 6 UCS and tooth wear rate

D. Correlation between Tooth Wear Rate and Rock Abrasivity Index

The relation between the tooth wear rate and the rock abrasivity index is given in Figure 7. It shows that increasing rock abrasivity index increase the wear rate of the drill bit.

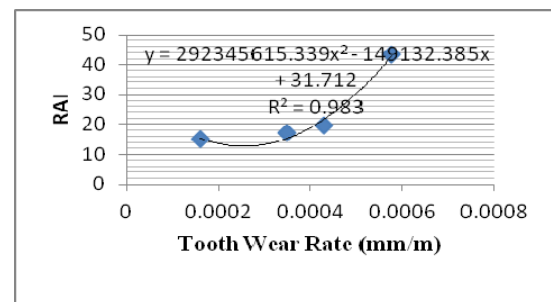


Fig. 7 RAI and tooth wear rate

E. Regression Model

Regression Model for Predicting Penetration Rate for Limestone Formation

The regression equation for predicting penetration rate in limestone formation is expressed in Equation 6

$$Pr = 4.583 - 1.052T + 0.029EQC + 0.046SiO_2 \quad (6)$$

Where, Pr = Penetration rate (m/min) Dependent Variable, T = Tensile strength (MPa), EQC = Equivalent Quartz Content (%), SiO₂ = Silica content (%) the regression model has multiple correlation of R = 1. Fig. 8 shows the plot of dependent variable against regression standardized predicted penetration value for limestone.

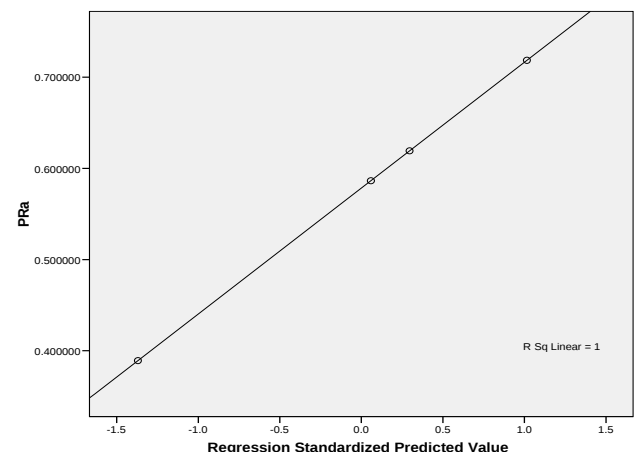


Fig. 8 Dependent variable (penetration rate) against regression standardized predicted value for limestone.

F. Regression Model for Predicting Tooth Wear Rate of Limestone

The regression equation for predicting tooth wear rate of limestone is expressed in Equation 7 and the coefficients are presented in Table VI.

$$W_G = -8.127 + 2.7T - 1.29EQC - 0.024SiO_2 \quad (7)$$

Where, W_G = Wear rate of bit tooth (mm/m), T = Tensile Strength (MPa), EQC = Equivalent Quartz Content (%), SiO_2 = Silica Content (%)

G. Regression Model for Predicting Bearing Wear Rate of Limestone

The regression equation for predicting bearing wear rate in limestone is expressed in Equation 8 and the coefficients are presented in Table VII.

$$W_B = -10.296 + 3.453T - 0.203EQC - 0.027SiO_2 \quad (8)$$

Where, W_B = Bit bearing wear rate (mm/m), T = Tensile Strength (MPa), EQC = Equivalent Quartz Content (%), SiO_2 = Silica Content (%).

TABLE VI COEFFICIENTS FOR TOOTH WEAR RATE MODEL

		Unstandardized Coefficients		Standardized Coefficients	Correlations		
		B	Std. Error	Beta	Part	B	Std. Error
1	(Const)	-8.127	.000				
	T	2.700	.000	.2473	.852	1.000	.158
	EQC	-.129	.000	-.1824	.711	-1.000	-.148
	SiO ₂	-.024	.000	-.194	-.984	-1.000	-.041

The multiple correlation coefficients, R is given as 1 and the plot of dependent variable against regression standardized predicted value is presented in Fig. 9.

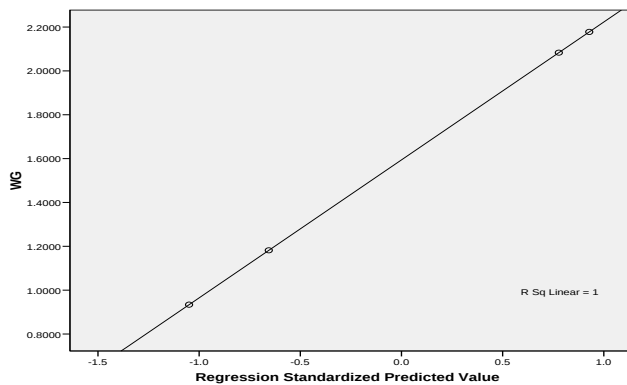


Fig. 9 Dependent variable (Tooth Wear Rate) against regression standardized predicted value.

TABLE VII COEFFICIENTS FOR BEARING WEAR RATE MODEL

		Unstandardized Coefficients		Standardize Coefficient	Correlations		
		B	Std. Error	Beta	Part	B	Std. Error
1	(Consts)	-10.296	.000				
	T	3.453	.000	.3349	.573	1.000	245.26
	EQC	-.203	.000	-.3041	.372	-1.000	152.78
	SiO ₂	-.027	.000	-.230	-.926	-1.000	22.17

The multiple correlation coefficients, R is given as 1 and the plot of dependent variable against regression standardized predicted value is presented in Figure 10

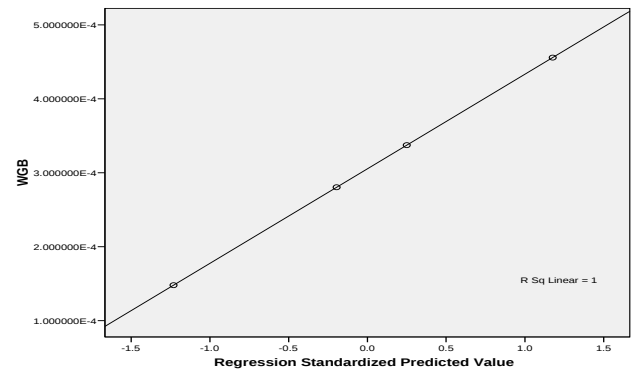


Fig. 10 Dependent variable (Bearing Wear Rate) against regression standardized predicted value.

H. Computer Programme Development

Using the regression model formulated, a computer programme application called LIMROCKWARE2010 was developed, in order to be able to compute the penetration rate, tooth and bearing wear rate, depth drilled per metre, estimate number of bits required and cost of drilling per metre when necessary rock input are supplied. The interfaces of LIMROCKWARE2010 Management Analysis are presented in Fig. 11 and 12. Reference [11] used empirical equations proposed by different researchers to develop software for computation of drilling and blasting parameters.



Fig 11. Opening interface of LIMROCKWARE2010

Fig.12 Computing interface of LIMROCKWARE2010

IV. CONCLUSIONS

This paper has established that dominant rock properties such as the uniaxial compressive strength, tensile strength, silica content, equivalent quartz content and rock abrasivity index affect the performance of tri-cone bit in limestone formation. The results of the statistical correlation matrix also confirmed that the plots of each of the rock properties against the tri-cone bit performance variables have high coefficient of correlation. The computer programme, developed from the regression models generated for the penetration rate, tooth and bearing wear rate using C# programme software will compute the penetration rate, tooth and bearing wear rate, depth drill per bit, number of drill bits required and drilling cost in Naira per metre.

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